

Design and Construction of the Hybrid Arch Bridge



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Abstract: Hae-oreum Bridge is a cable supported arch bridge with a steel-concrete hybrid deck. The bridge is the half-through arch bridge located on the linking way of Incheon Bridge which connects Incheon international airport to Songdo cosmopolitan city. It measures 213 m in total length and 120 m in the center span. The side spans consist of prestressed concrete box (PC box) girders and the center span is designed as steel-concrete composite girders. In design practice, one of the main issues is to reduce the horizontal force transmitted to pile foundations because the deep foundation using cast-in-place concrete piles was adopted to overcome the soft ground condition in the bridge site. To control the horizontal force, tie cables are installed inside of edge girders and their prestresses are determined to minimize the horizontal force on pile foundations at the construction stage of the additional dead load. Different with general cable supported arch bridges, hanger cables are designed to be initially prestressed and the prestressed force of each hanger cable is estimated to restrict the displacement of the edge girder due to the first dead load. Throughout this paper, the bridge design and construction is briefly described.

Keywords: hybrid arch bridge, fork type anchorage, induction heating, unbraced steel tube, tie cable

1. INTRODUCTION

Hae-oreum bridge is a part of the second construction site of the linking way of Incheon Bridge and it is located at the East side of Incheon Bridge. The project was started on January 2005 and will be opened to traffic in October 2009. The project consists of three different types of bridge; prestressed concrete (PC) box girder bridge by the incremental launching method, PC box girder bridge by the full staging method, and the steel-concrete hybrid arch bridge.

Of those bridges, Hae-oreum bridge is designed as a steel-concrete hybrid arch bridge. Architectural considerations played an important role in the plan of the bridge concept. Because the construction site of the bridge is the development area of Songdo cosmopolitan city, it was required that the shape of bridge should be balanced with the surrounding high-rise building and the bridge should offer a landmark for the region. In addition, it was also required to secure a long span because of the further construction plan of wide road and subway under the bridge. Therefore, the bridge was arranged as a half-through three span arch bridge with inclined cable planes.

This paper provides general information on the design and the construction of the Hae-oreum bridge.



Figure 1: Location of Hae-oreum bridge



Figure 2: Rendering of Hae-oreum bridge

2. OUTLINE OF HAE-OREUM BRIDGE

As noted, the Hae-oreum bridge is a half-through hybrid arch bridge and its general arrangement is shown in Fig. 3. The main girder section consists of three spans, 46.5m, 120m, and 46.5m, and measures 213m in total length. The main girder section is shown in Fig. 4 and table 1 presents the design specifications.

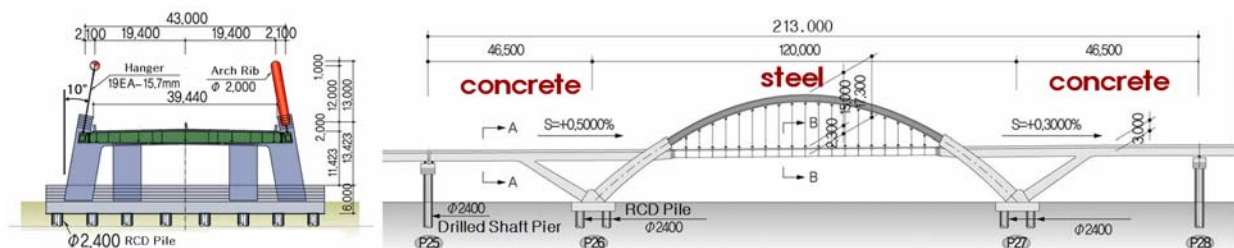


Figure 3: General arrangement

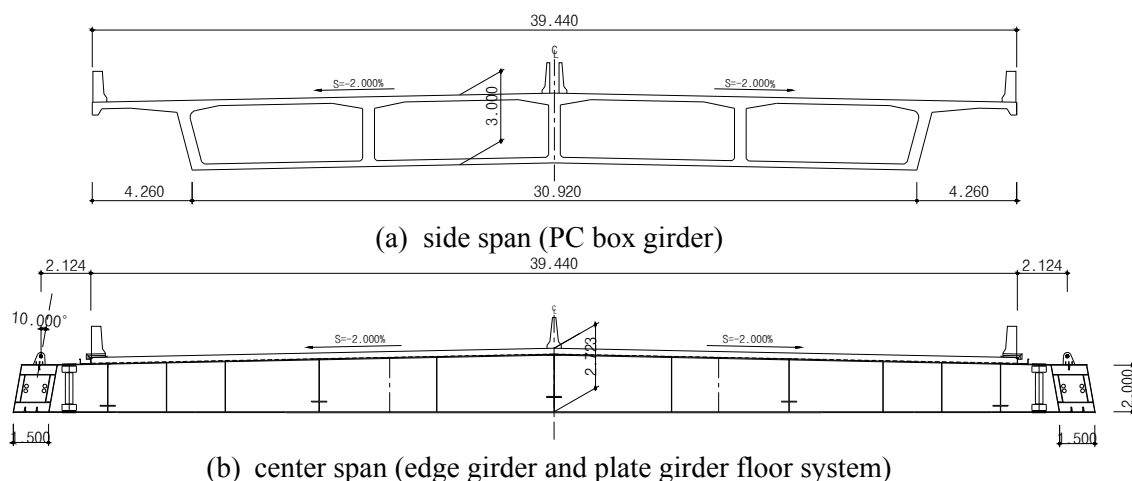


Figure 4: Main girder section

Because of the soft ground condition on the construction site, the main problem is how to reduce the horizontal force transmitted to the foundation of arch ribs. In addition, the width of bridge is about 43m and the ratio of length to width of steel girder region is less than 2.0. This means that two dimensional behavior needs to be considered when the main girder of center span is analyzed and fabricated. This is also made it difficult to control the configuration shape of main span. In order to overcome such problems, following alternatives were adopted.

- (1) steel-PC girder hybrid system: PC box girder for both side spans, steel box edge girder and plate girder floor system for the center span
- (2) applying counter force against the horizontal force: installing and prestressing tie-cables inside of edge girders
- (3) rearrangement of construction stage: closing the steel girder and PC girder after each span is completed

Table 1: Design specifications

Items	Description
Span length	$46.50 + 120.00 + 46.50 = 213.00$ m
Width	39.44 ~ 39.51 m
Girder	Side span: PSC box girder, $H=3.00$ m, $f_{ck}=40$ MPa Center span: Edge girder – Steel box, $H=2.00$ m, SM490Y
Arch rib	Material and cross sectional shape: Unbraced steel tube, TMC570 Dimensions: $\Phi 2.00$ m, $t=30\sim 40$ mm
Hanger system	Cable: Multi-strand cable, $\Phi 15.7$ mm-7strand, 19EA, $f_{pu}=1770$ MPa Anchorage: Pin-socket system
Tie-cable	$\Phi 0.6$ "-43strand, 3EA/Edge beam
Pier	Concrete box: $f_{ck} = 40$ MPa
Foundation	Footing Concrete: $f_{ck} = 40$ MPa Prestress tendon: SWPC 7B $\Phi 0.6$ "-22strand, 16EA RCD pile: $\Phi 2.4$ m, 16EA, $f_{ck} = 35$ MPa

3. CHARACTERISTICS OF BRIDGE DESIGN

3.1 Hybrid System

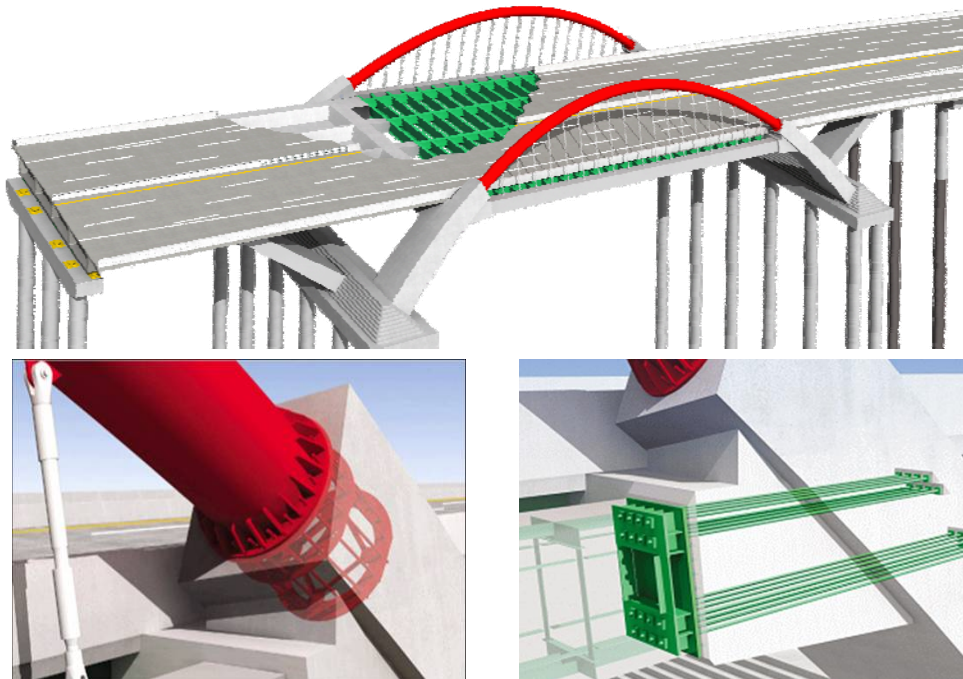


Figure 5: Hybrid system

The hybrid system of Hae-oreum bridge is shown in Fig. 5. The front bearing plate method was adopted to connect the center span to side spans. In order to minimize the bending moment at the connection part, the linking stage was also arranged after completing each span respectively. Since the superstructure of

the main and side span is completely installed before linking the main span to side spans, the bending moments at the connection part due to the self-weight of deck system for both main and side spans are omitted.

3.2 Tie Cables and Foundations

Hae-oreum Bridge is the special case of arch bridges because the foundation of the bridge is erected on the soft ground. Therefore, the most important issue of the bridge is how to control the horizontal forces of the foundation. To reduce the horizontal forces transmitted to the foundation, the tie cables are designed to be installed inside of edge girders and to be anchored at the concrete arch rib after prestressing. Fig. 6 illustrates how to control the horizontal force using tie cables.

The total amount of horizontal force was 24,325 kN if the tie cables were not adopted. Applying the tie cable system, the horizontal forces at the specified construction stages are reduced as shown in Table 2.

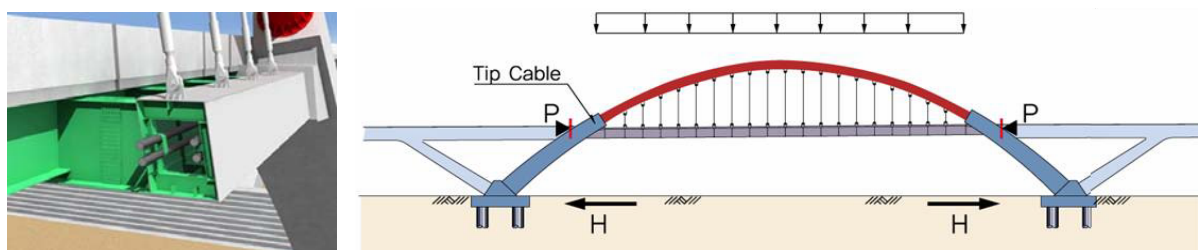


Figure 6: Mechanism of the reduction of horizontal force

Table 2: Horizontal force at the foundation

Construction stage	1 st Prestressing of tie cable	Installing the hanger cable	2 nd Prestressing of tie cable	Additional dead load
Horizontal force at the foundation (kN)	-12,671	8,333	1,867	3,203

Four tie cables are installed inside of each edge girder. Three of them are used to reduce the horizontal force and the remainder is for the rehabilitation. Two of those tie cables per each edge girder were stressed before erecting hanger cables and the rest one was tensioned after removing the temporary supports.

3.3 Hanger Cables

The multi-strand cables with the pin type anchorage are used for the hanger system as shown in Fig. 7. The pins attached to each end of a hanger are orthogonally arranged to release the secondary stresses due to the bending at the ends of hanger.

For the ordinary cable supported arch bridge, cables are freely hanged between arch rib and stiffening girder when cables are installed, and the cable forces are introduced when the arch ribs and stiffening girders are deflected due to dead loads. In this case, the camber of arch ribs and stiffening girders need to be considered when those are fabricated.

In the case of Hae-oreum bridge, hanger cables are designed to be initially prestressed when those are installed. The initial cable force of each cable was estimated to restrict the displacement of stiffening girder at the location of bent supports due to dead loads. The cable force becomes the maximum (max. $0.28f_{pu}$) when each cable is erected and all cable forces remains a similar magnitude after the construction is completed. Fig. 8 shows the history of cable forces.

3.4 Camber Control

As noted, the width of bridge is relatively wide to the length of the center span. If the connection part of girders were performed before erecting cables, the displacements would be changed not only along the longitudinal direction but transverse direction, and the fabrication of each cross beam and stringer would be very complex.

In the case of Hae-oreum bridge, center and side spans were planned to be connected after the erection of each span and cable was completed, and the initial cable force which was estimated from the stage

analysis was applied in order to control the displacement of edge girders due to dead loads. Adopting this design concept, the deformed shape of center span after erecting cables becomes a cylindrical shape as shown in Fig. 9.

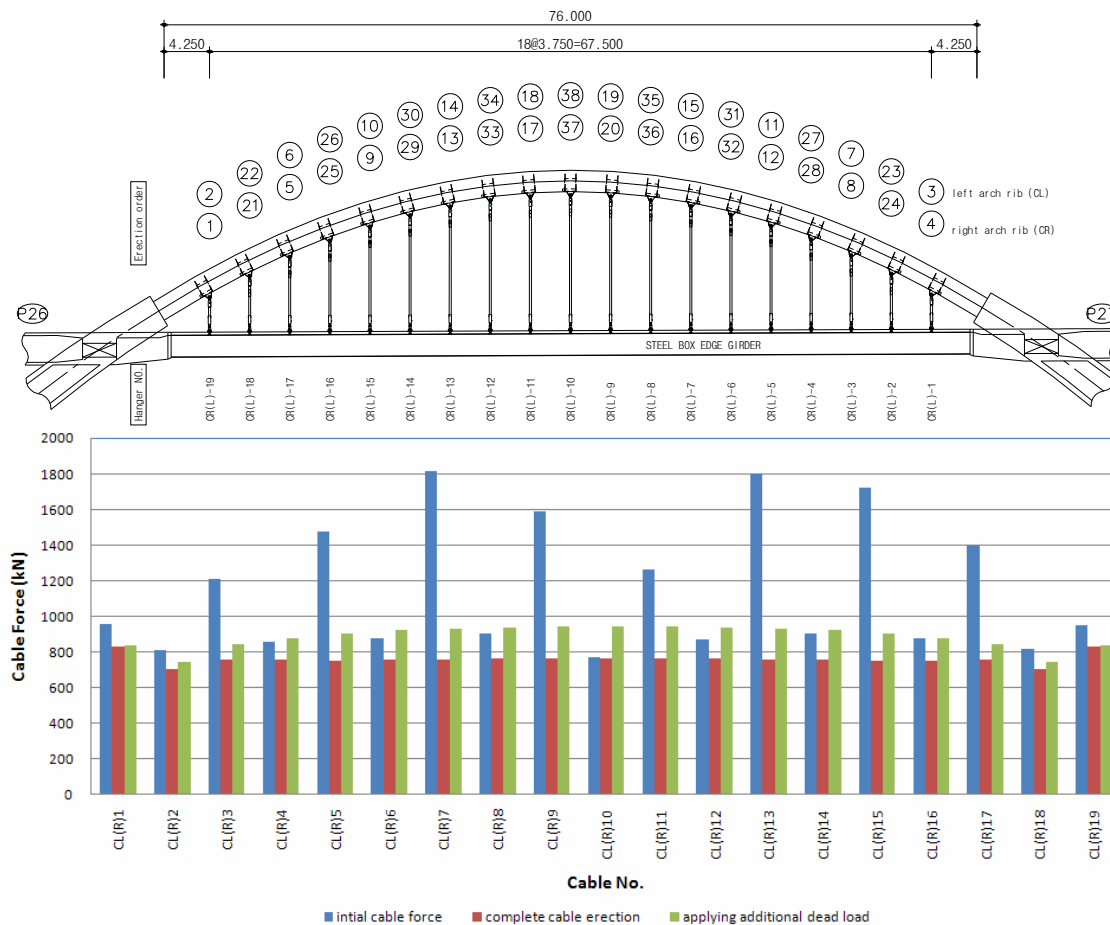


Figure 8: History of cable forces



Figure 7: Pin type anchorage system

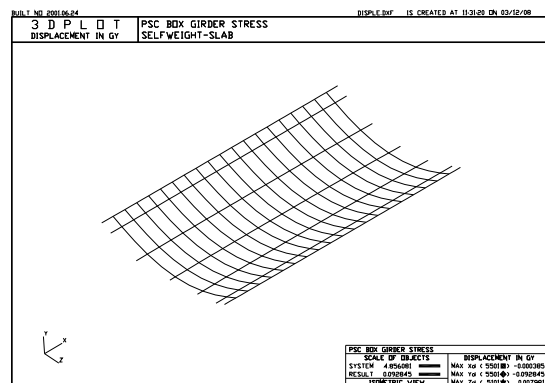


Figure 9: Deformed shape of center span (analyzed by 3DS program)

4. CONSTRUCTION OF THE BRIDGE

4.1 Outline of the Erection

The outline of the erection is illustrated in Fig. 10. Inclined piers, concrete arch ribs, and side spans are erected by the full staging method and deck system of center span is built up by the segment before connecting steel girders to the PC girder. After the erection of steel arch ribs and the deck slab of center

span, three tie-cables are installed inside of edge girder. Two of tie-cables are prestressed before erecting hanger cables and 2nd tensioning work of remaining tie cables is conducted after erecting hanger cables. Finally, the linking part is installed and concreted.

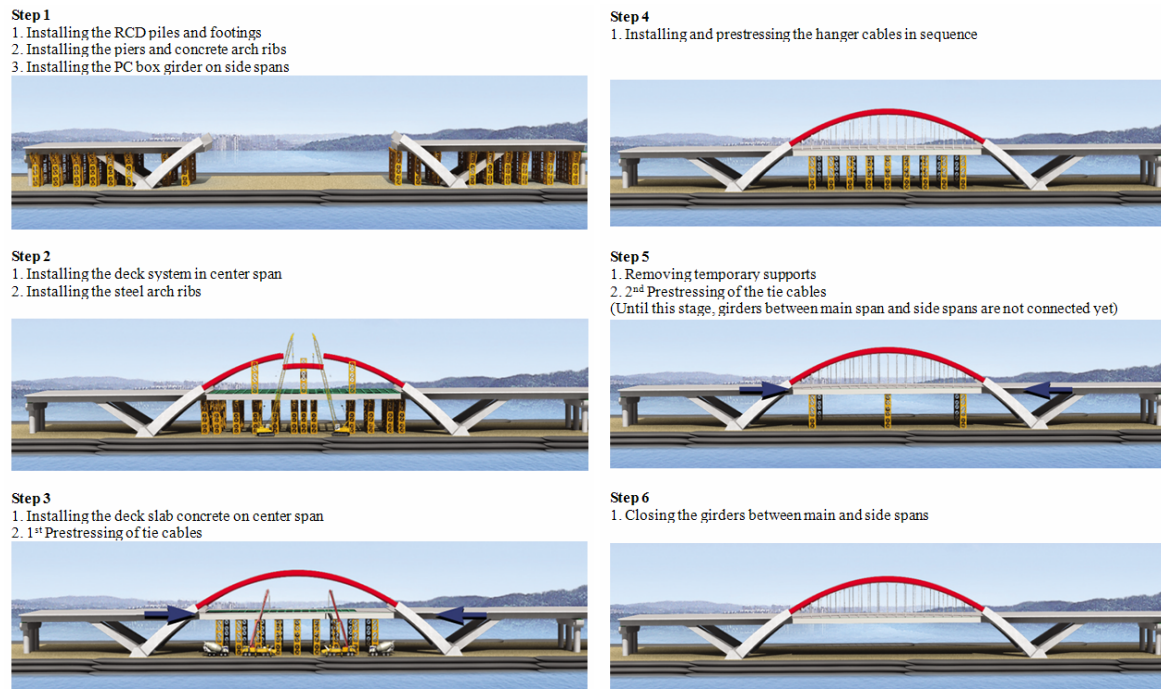


Figure 10: Procedure of the erection of Hae-oreum bridge

4.2 Substructure

Foundation of the arch bridge consists of twenty four RCD (reverse circular drilled pile) piles and concrete footing as shown in Fig. 11. The RCD pile is 2.4m in diameter and it is placed more than 40m depth to ensure its placing on bedrock.

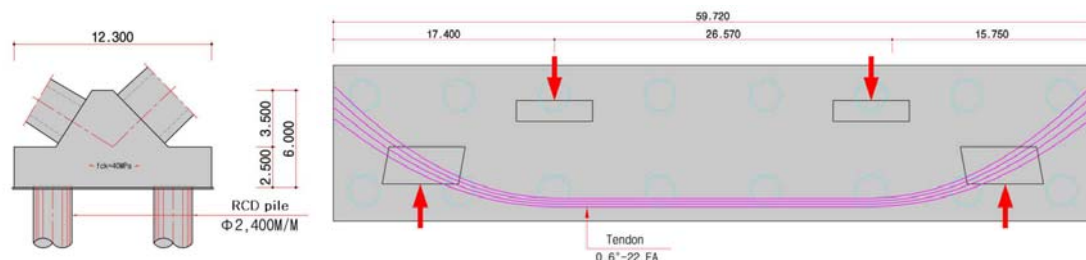


Figure 11 Footing (unit: m)

The amount of reinforced concrete to be cast in the air for the Hae-oreum bridge's footing totaled about 2,700m³. To minimize the hydration temperature during curing, a low-heat cement was used and concreting the footing was divided from two steps; 2.5m for the first lot and 3.5m for the second lot. In addition, the pipe cooling system was adopted for six curing days.

As shown in Fig. 11, the inclined pier from side span and the concrete arch ribs are connected eccentrically with the footing because the arch ribs are inclined 10° to the roadway from the vertical. Thus, the forces transmitted to the footing from piers and arch ribs cause the lateral deformation of the footing. To reduce the effect of the couple due to eccentrically transmitted forces, the tendons were embedded in the footing and prestressed.

Inclined piers and concrete arch ribs with the hollow box shape of cross section were constructed by the full staging method. Because the cross sectional dimensions change along the member axis, it is difficult to place and to take off the inner form. Thus, EPS (expanded poly-styrene) blocks were used as the inner form. Fig. 12 shows the falsework of inclined piers and concrete arch ribs.



Figure 12: Falsework of piers



Figure 13: Erection of steel girders

4.3 Steel Girders

For the center span of the Hae-oreum bridge, the edge girder and the steel plate girder floor system was used as shown in Fig. 4. Two edge girders were made of parallelogram steel box and placed each side of the center span, and the temporary supports were arranged along the edge girder. The end segment of edge girder with 2.7m in length was placed first and the large segment with 30m in length was erected by two crawler cranes, and the segments were welded on site.

After erecting edge girders, the cross beams were lifted and connected to the edge girders by high tension bolts. Fig. 13 shows the erection of steel girders.

Because the temporary supports were placed only under the edge girder, the rotational displacement of edge girder occurs during erection. To allow the rotation of the edge girder, the oil pressure jack with a spherical support was used.

4.4 Arch Rib

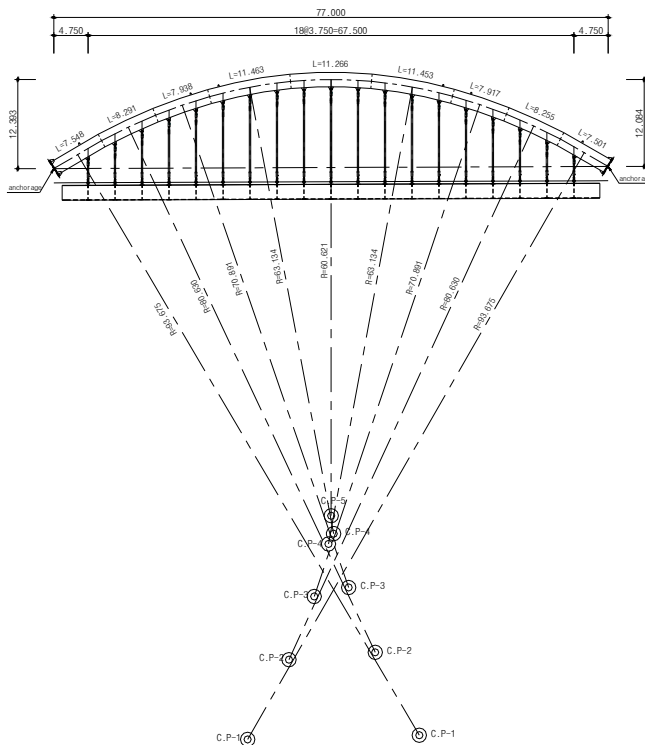


Figure 14: Radius of curvature of the arch rib



Figure 15: Fabrication procedure of the arch rib

Since the arch rib is designed as an unbraced steel tube with 2.0m in diameter and each segment has the different radius of curvature as shown in Fig. 14, it is difficult to fabricate the bended arch rib. In the Hae-oreum bridge, the induction heating and bending method was used to prepare the segment of arch ribs. Induction heating is a non-contact heating process. It uses high frequency electricity to heat materials that are electrically conductive. Since it is non-contact, the heating process does not contaminate the material being heated. It is also very efficient since the heat is actually generated inside the workpiece. This can be contrasted with other heating methods where heat is generated in a flame or heating element, which is then applied to the workpiece. Fig. 15 shows the fabrication procedure of arch rib using the induction heating and bending method.

Nine segments in each arch rib were fabricated, and segment No. 1 to 4 and No. 6 to 9 were welded to make large block in the field before lifting. Two cranes with a 4000 kN capacity were used to lift and place each large block of arch rib. Fig. 16 illustrates the erection of arch ribs.



Figure 16: Erection of arch ribs

4.5 Hanger Cable

Hanger cable system used in this project is a multi-stand stay cable with fork type anchorage block. The cable consists of strands ($\phi 15.7\text{mm}$ -19EA, $f_{pu}=1770\text{MPa}$), HDPE pipe, a protection tube, an adjustable fork, and a fixed fork. Strands are individually galvanized wires, sheathed, and greased by a HDPE material as shown in Fig. 17. Strands are anchored by using swages at the back of the anchorage block inside the adjustable and fixed fork. The adjustable fork is a mechanical threaded pipe using an adjustment rod which allows re-tensioning or detensioning operations. The fixed fork is a pin head without adjustment rod. Fig. 18 shows the Fork type anchorage (Freyssinet, 2009).

Prefabrication procedure of hanger cable is illustrated in Fig. 19. The reference length of cable used in the cutting process was established by considering the arch rib as-built position, the effect of temperature at the prefabrication stage and the anchorage length in addition to the result of the stage analysis. After cutting strands to the reference length of each cable and unsheathing the end of each strand by 70mm, strands were threaded inside top anchor block and specially fabricated sleeve was swaged at the end of each strand by the swaging device shown in Fig. 20. Following the prefabrication procedure, hanger cable was prepared as shown in Fig. 21.

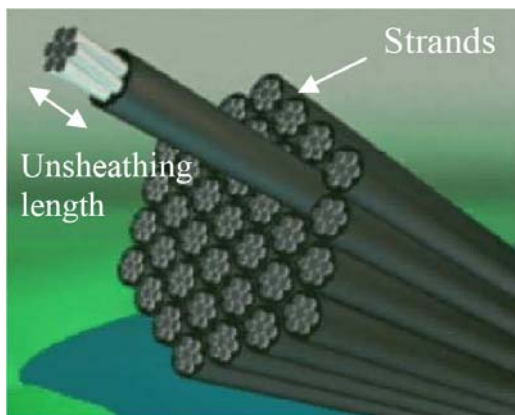


Figure 17: Strands

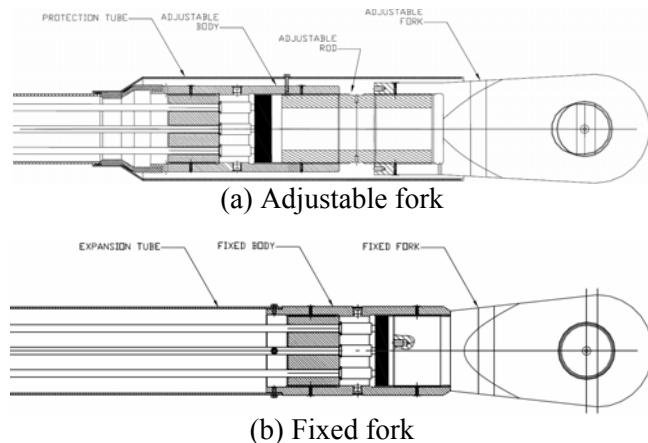


Figure 18: Fork type anchorage

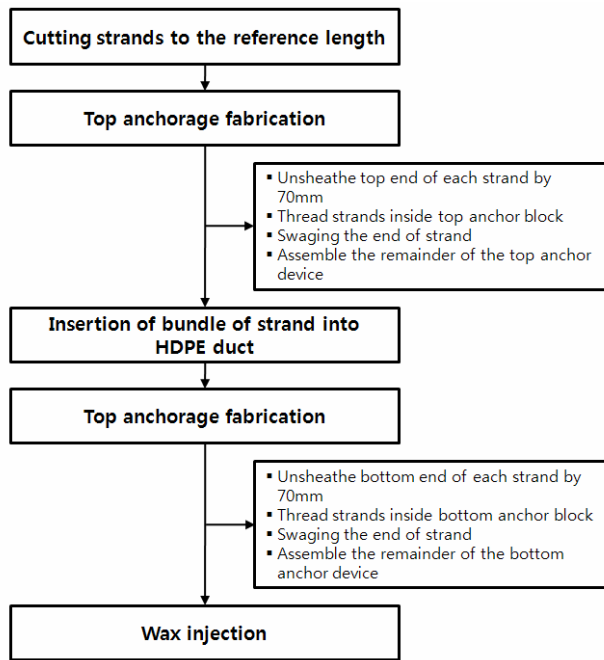


Figure 19: Prefabrication procedure



Figure 20: Swaging



Figure 21: Prefabricated hanger cable

The prefabricated cable was hoisted and connected to the top and bottom gusset by pin axle, and the tensioning device shown in Fig. 22 was installed to stress the cable. The lower part of the tensioning device was hung on the anchor pin and the upper part was placed at the top of the adjustable body. Once pressing the oil jacks installed to the top of the tensioning device up to the established cable force, the cable was pulled down and the adjustable nut was tightened.

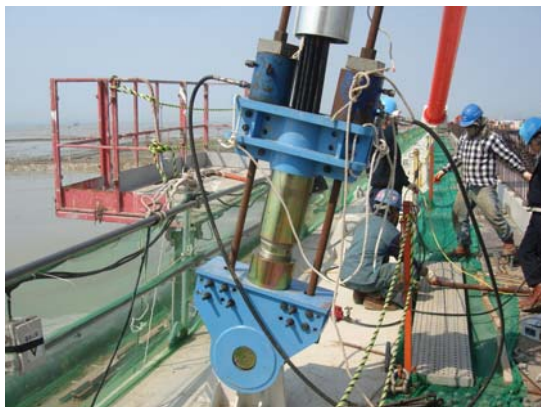


Figure 22: Tensioning device



Figure 23: Cable stressing

4.6 Connection of Girders

As noted, the front bearing plate method was adopted to connect the center to the side spans girders. Closing the steel and PC box girder was performed after the tie cable was completely stressed and the

temporary supports were removed. At this stage, about 300mm gap remains between steel girder and PC box girder as shown in Fig. 24. After hardening the cast-in-place concrete the gap between steel and PC girders, the connection work is completed by stressing the threaded bars. However, the failure of concrete placed in the space can occur before the bars are prestressed because the center span contracts and elongates about 5mm at each end when the variation of temperature is 10°C

For this reason, the rapid hardening mortar ($f_{ck}=40\text{MPa}$) was used to connect the steel and PC girders and the connection work was performed at midnight in order to develop the strength of concrete fast during the steady temperature. The mortar used to the connection work is a pre-mixed material and the compressive strength of the mortar was developed over 30MPa within 3 hours.

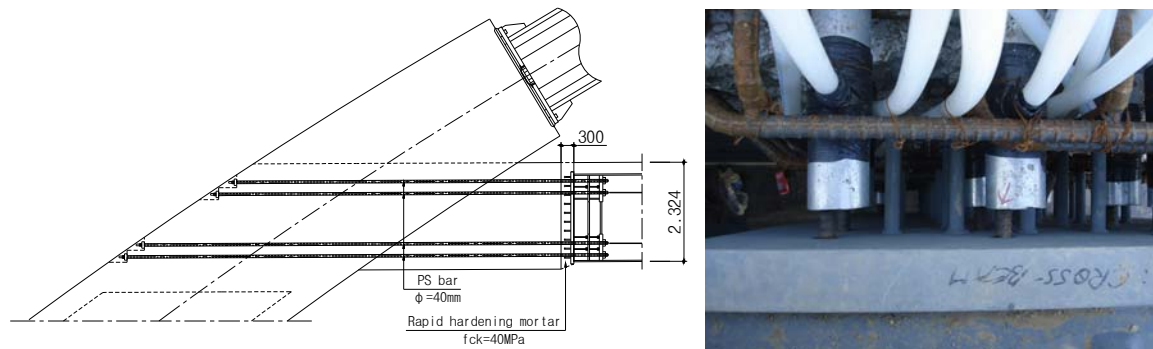


Figure 24: Connection part

5. CONCLUDING REMARKS

The bridge provided in this paper is not as a large structure as a cable-stayed bridge or a suspension bridge which have been constructed recently. However, it is very meaningful that the arch bridge is constructed by overcoming the week environmental conditions for an arch bridge.

Recently, countries and cities around the world have chosen memorable structures or monuments to attract business and tourists. The bridge described in this paper is aimed not only to connect Incheon international airport to Songdo cosmopolitan city but also to play a role of the landmark bridge of the new city. The linking way as well as Incheon Bridge will be to make it easier to access to the international airport and will be helpful to grow economic liberalization in Southeast Asia.

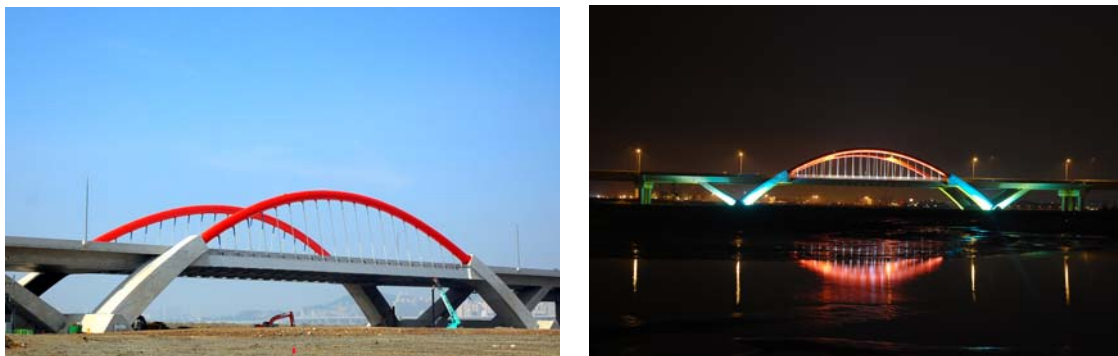


Figure 25: View of closed Hae-oreum bridge

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